8-3E

TWO-PHASE FLOW IN VERTICAL AND INCLINED ECCENTRIC FLOW

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Objective: to collect experimental data of gas/liquid flow under conditions representative of well-control operations for horizontal wells.

Introduction

Blowout prevention is an important aspect in today's drilling industry. The use of simulators for personnel training improves the skills of those responsible for effectively conducting well-control operations. To enhance the reliability of such simulators and correctly predict the surface volume and pressures at the choke, a good understanding of the behavior of the gas/liquid flow is required. In addition to the complexity inherent to two-phase flow theory, the following parameters are specific to well-control situations:
1- The presence of a non-Newtonian fluid (the mud);
2- Occurrence of flow in an annulus;
3- Inclination angles with the vertical that can vary from 0 to 90 degrees.
The last item is of particular importance due to the increasing popularity of horizontal wells.

Nakagawa (1990) performed an experimental and theoretical study of gas/liquid flow in an annular space positioned at inclinations of 0° to 80° from the vertical. Water and two different mixtures of water-bentonite were used as the liquid phase and a 0.61 specific gravity natural gas. A typical result obtained in his study is shown in Figure 1, where the gas concentration α is plotted against the superficial gas velocity Usg. It can be seen that his studies did not cover the region of gas velocities smaller than 0.4 m/s.

Johnson and White (1991) used an apparatus similar to that of Nakagawa, for pipe flow, and performed experimental tests on the flow of gas/water and gas/polymer solution to simulate the drilling fluid. A simplified version of a typical result obtained can be seen in Figure 2, where the true gas velocity Ug is plotted versus the mixture velocity Um. The two regression lines correspond to the different gas fractions studied. In this work the smallest mixture velocity considered was 0.28 m/s.

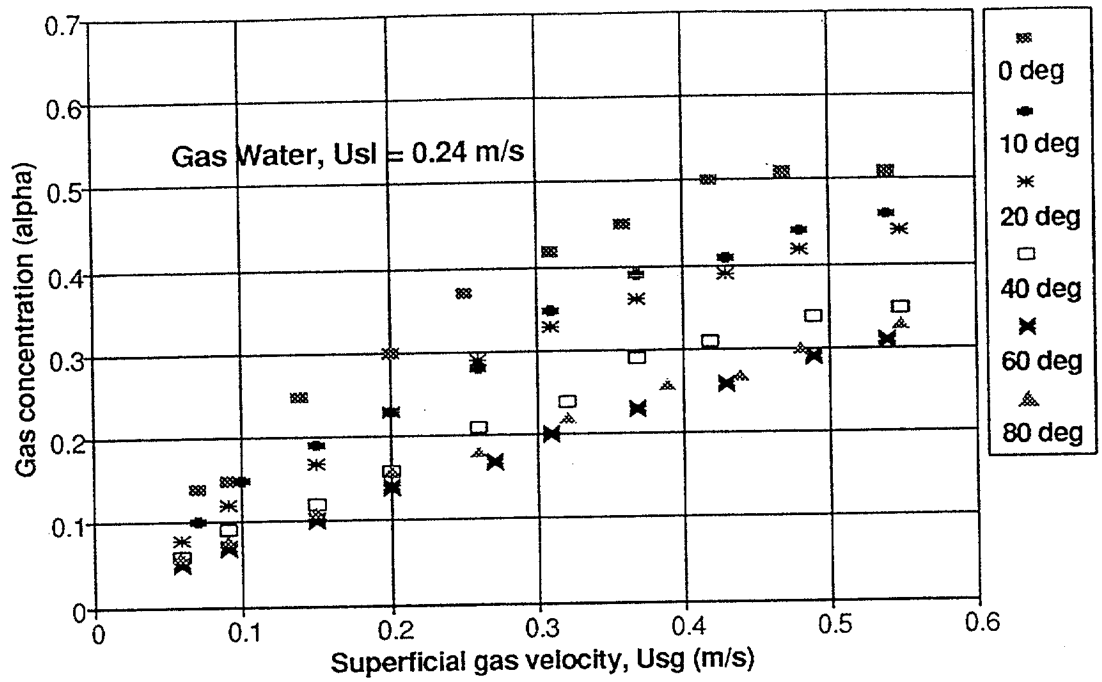


Figure 1 - Example of results obtained by Nakagawa (1990).

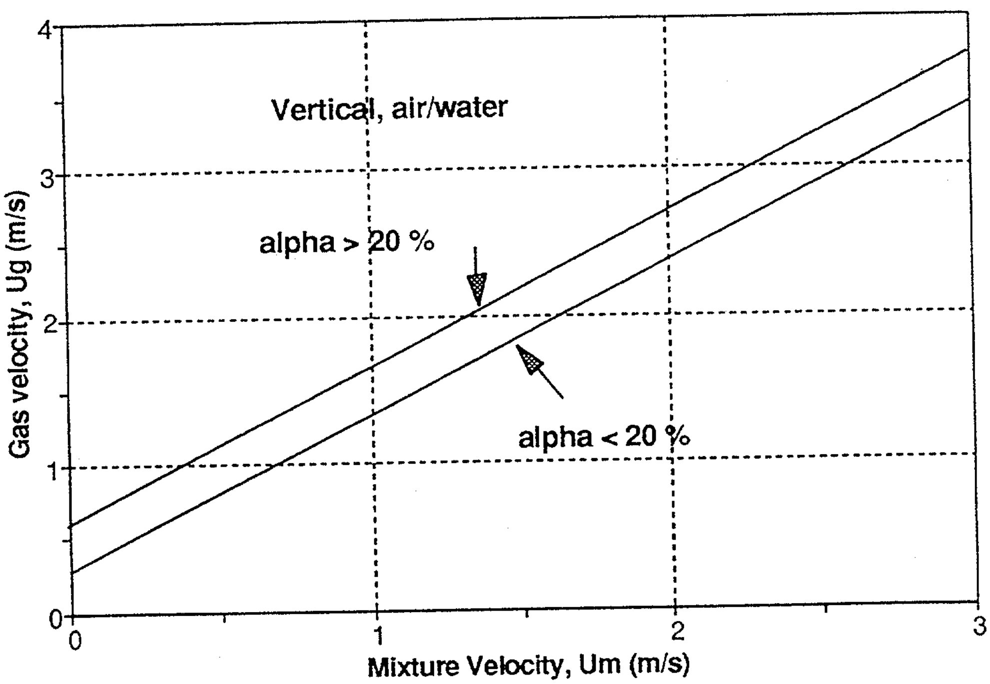


Figure 2 - Example of results obtained by Johnson and White (1991).

Considering this lack of information in the lower range of mixture velocity and gas concentrations, which are also found in well control procedures, it was decided to conduct experimental tests to generate the necessary data and verify the validity of the previous correlations.

Experimental Apparatus and Procedure

The equipment used was the same one described by Nakagawa and is schematically represented in figure 3. The liquid is handled in a system that comprises a 300 bbl tank, a centrifugal pump that supercharges a triplex pump and a 2" pipeline. Gas is delivered to the facility in a 6" pipeline, at approximately 650 psi. A remotely operated actuator and a pressure controller were installed in the gas system to improve flow rate measurements and control. An orifice meter is responsible for providing gas flow rates. The control of the flow is by manually adjusting the existing valves and remotely by actuating in a flow control valve. The flow loop is a combination of two 6" ID pipes connected in a U shape, with one of them having a 2 3/8" OD pipe in its interior to simulate the drillpipe. There are 3 differential and one absolute pressure transducers installed along the annular section and one temperature transducer. Four valves are placed in the system to allow the direct measurement of the gas and liquid fraction by trapping the flowing mixture.

An experimental run starts by positioning the loop at the desired inclination angle. A process control computer is activated to automatically control gas and liquid flow rates to achieve the expected superficial velocities. After the system reaches stability, which is confirmed by the constancy of the differential pressure readings, the data acquisition computer is started to collect the variables being monitored: pressure, differential pressure, temperature and flow rates. After one minute approximately the 4 valves are closed with the data acquisition system still operational, for another minute. Then other gas and/or liquid velocities are tested until the test matrix is finished.

A total of 144 tests were performed: 72 with gas/water and 72 with gas/mud mixtures, for the inclinations of 0, 10, 20, 40, 60 and 80 degrees with the vertical. The superficial liquid velocities were 0.06, 0.10 and 0.26 m/s. The superficial gas velocities were 0.02, 0.04, 0.09 and 0.12 m/s. The mud was a 8.62 ppg water-bentonite mixture with plastic viscosity of 10 cp and yield point of 6 lbf/100 sq ft.

Data analysis equations

Before presenting the results, the most important equations used to analyze the data and calculate gas fraction and velocity will be summarized.

The superficial velocity is defined as the velocity of each component if flowing alone in the system. Therefore the gas superficial velocity will be given by :

$$U_{sg} = \frac{Q_g}{A_f} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

where Q_g is the gas flow rate and A_f is the cross sectional area of the medium.

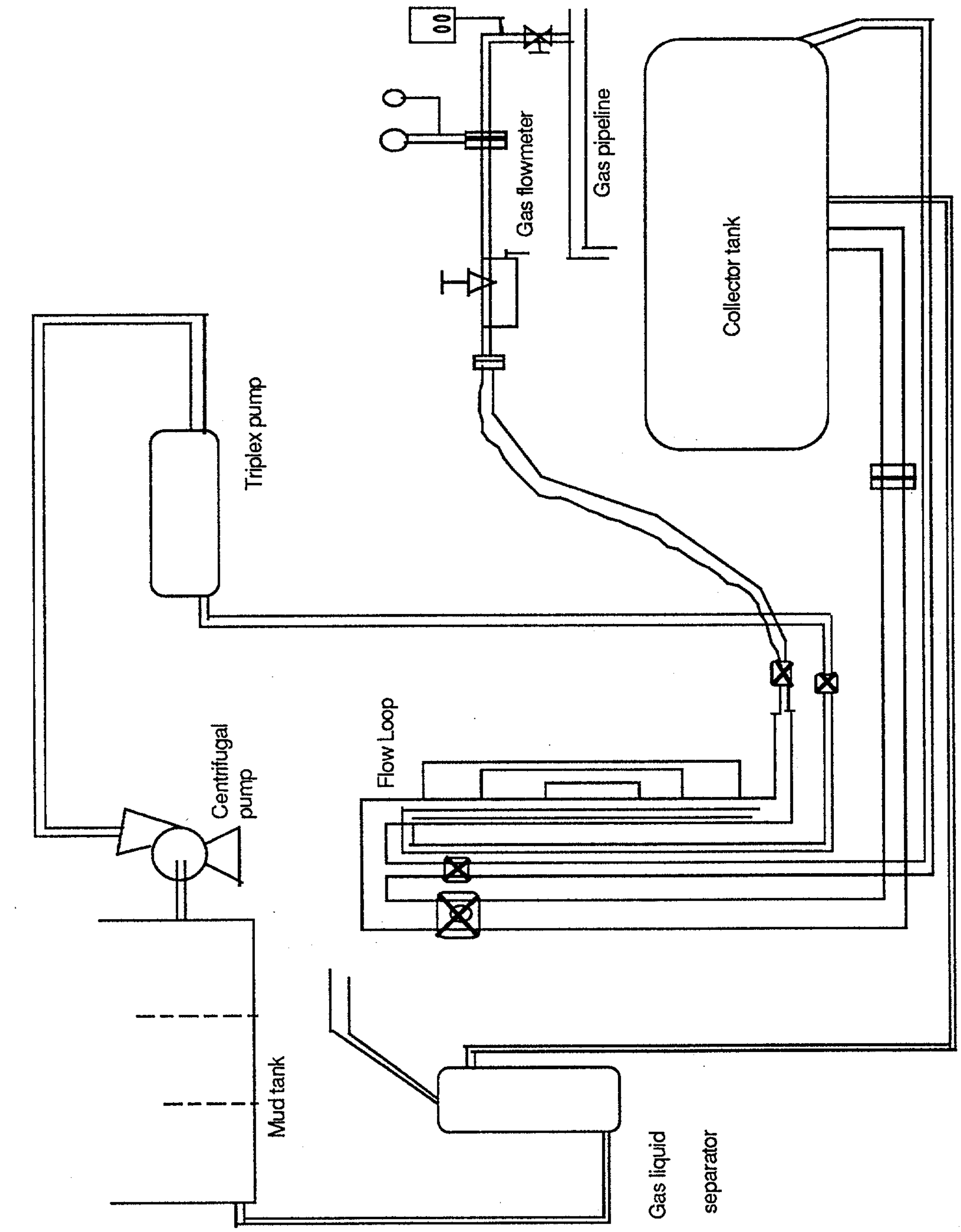


Figure 3 - Schematic of Experimental Equipment

Similarly, the liquid superficial velocity will be:

$$U_{sl} = \frac{Q_l}{A_f} \qquad \text{.........................} \qquad (2)$$

Mixture velocity is defined as the sum of the superficial velocities:

$$U_m = U_{sg} + U_{sl} = \frac{Q_g + Q_l}{A_f} \qquad \text{.............} \qquad (3)$$

Due to slippage between the gas and liquid phases, the true velocity that each one will have is different from the superficial velocity. If we call the volumetric gas concentration as α, the true average gas velocity is defined by:

$$U_g = \frac{U_{sg}}{\alpha} \qquad \text{..........................} \qquad (4)$$

The liquid volumetric fraction is usually called holdup and in a two-component system is obtained by

$$H_L = 1 - \alpha \qquad \text{............................} \qquad (5)$$

When the slippage between the phases is neglected, the same fractions can also be defined. Lambda is the no-slip liquid concentration, and can be obtained by:

$$\lambda = \frac{U_{sl}}{U_m} \qquad \text{................................} \qquad (6)$$

The density of the mixture flowing in the annulus can be computed by the following volumetric balance:

$$\rho_s = \alpha\,\rho_g + (1-\alpha)\,\rho_l \qquad \text{......................} \qquad (7)$$

Therefore the gas fraction will be:

$$\alpha = \frac{\rho_l - \rho_s}{\rho_l - \rho_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

By applying the energy conservation equation, neglecting the acceleration component and considering a two-phase friction factor, the density of the mixture can be determined by:

$$\rho_s = \frac{-DP_{tot} + L\cos\theta}{L\cos\theta + \dfrac{f\,U_m^2\,L}{(Do - Di)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where DP_{tot} is the pressure drop given by the transducer, L the distance between the observed points, Θ the inclination of the loop with the vertical, f the friction factor, Um the mixture velocity as defined above, Do the internal diameter of the outer pipe and Di the external diameter of the inner pipe.

The other equation used to determine the gas fraction is obtained by analyzing the pressures in the system when the valves are closed, and was derived by Nakagawa (1990) as:

$$\alpha = 0.002\,(20.77 - 0.148\,\theta)$$

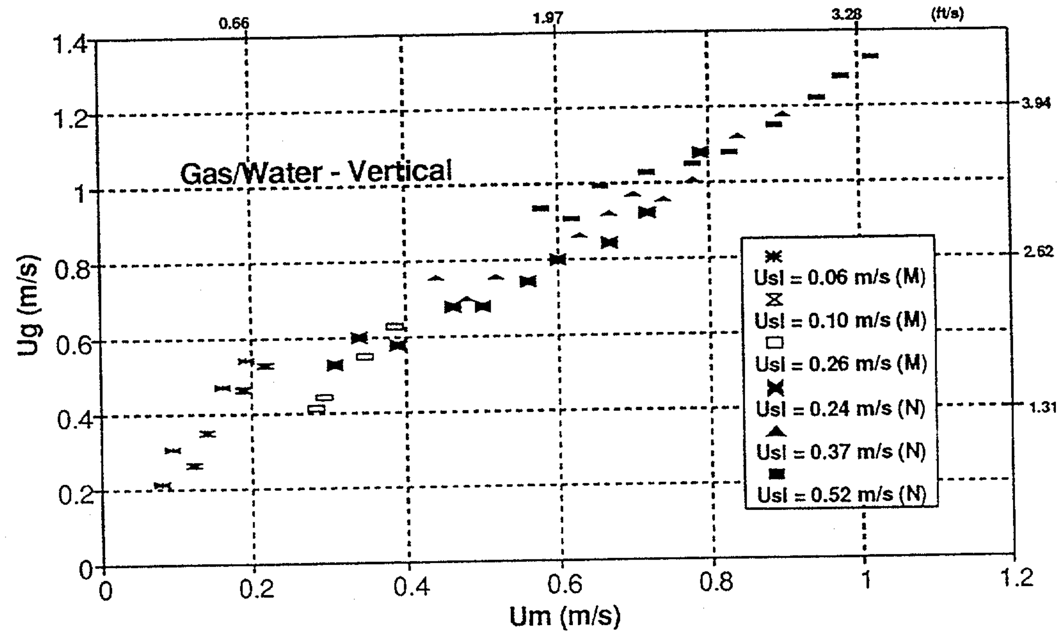
$$+ 0.019\,\left(\frac{\rho_l - 8.33}{\rho_l} + \frac{DP_1}{0.052\,\rho_l\cos\theta}\right) \quad \ldots\ldots\ldots (10)$$

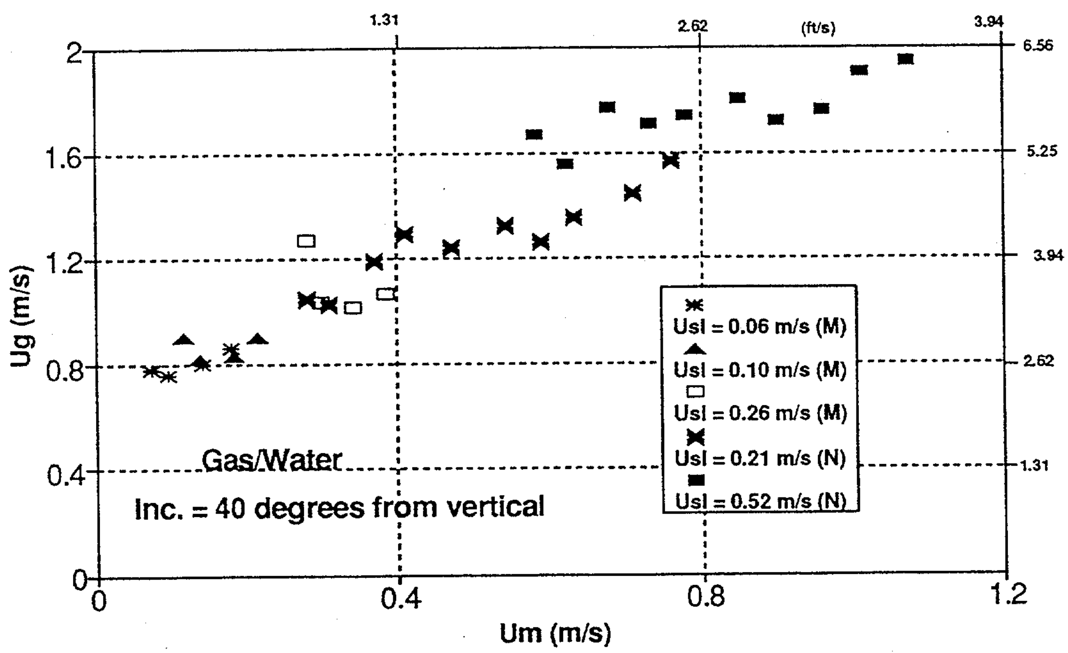
Rho_l is the density of the liquid being used.

Experimental Results

Here are presented the most representative sets of each mixture and inclination studied. Some of the graphs also display the results obtained by Nakagawa in order to better visualize how they correlate with the ones currently obtained.

For gas/water vertical flow, the true gas velocity is plotted versus mixture velocity in Figure 4. The new set of data indicate a higher slope and a smaller intercept than would be obtained by extrapolating the data obtained by Nakagawa. For the inclined tests, the plot at 40 degrees is shown in Figure 5 and can be considered similar to the results at 10, 20 and 60 degrees. The results at 80 degrees are also shown in Figure 6 since they indicate a slightly different trend, with a gas velocity smaller than expected.





Figures 4 and 5 - Plot of true gas velocity vs mixture velocity, gas/water flow, at 0 and 40 degrees inclination from vertical, for different superficial liquid velocities.

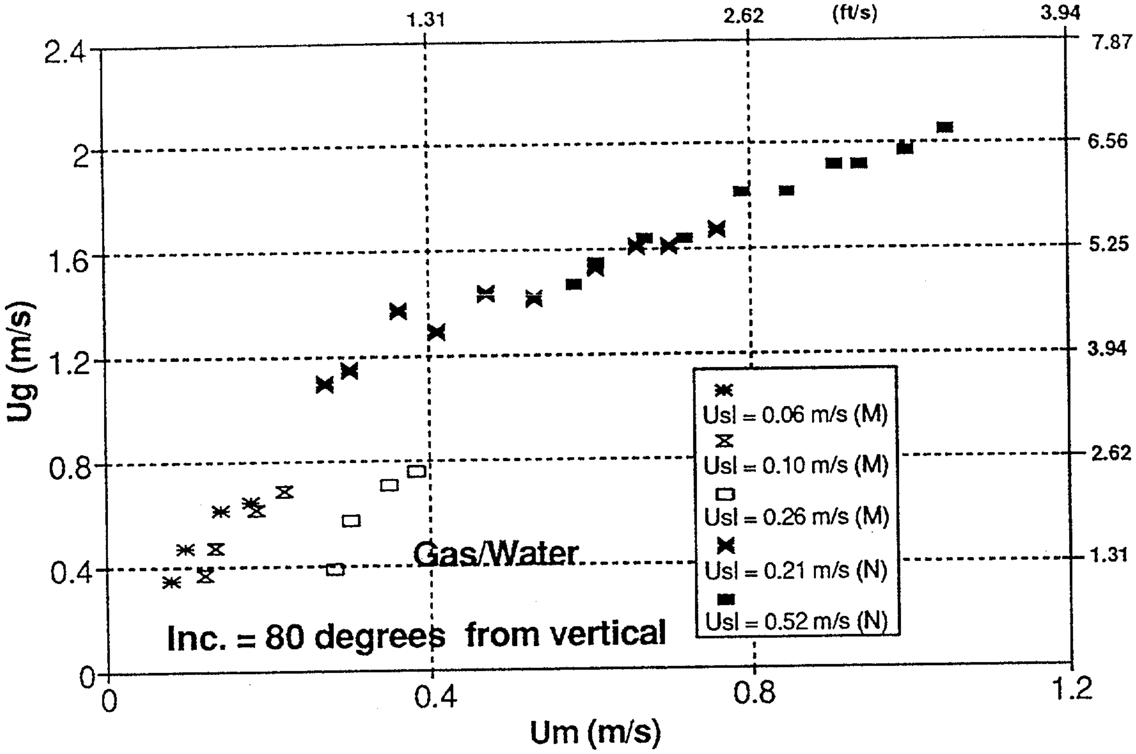


Figure 6 - Same as Figs. 4 and 5, at 80 degrees inclination from vertical.

For gas/mud flow, all the experiments showed a general tendency of lower gas velocities than those obtained by extrapolating the previous correlations. Figure 7 depicts the results and for the vertical configuration and Figure 8 for inclination of 40 degrees.

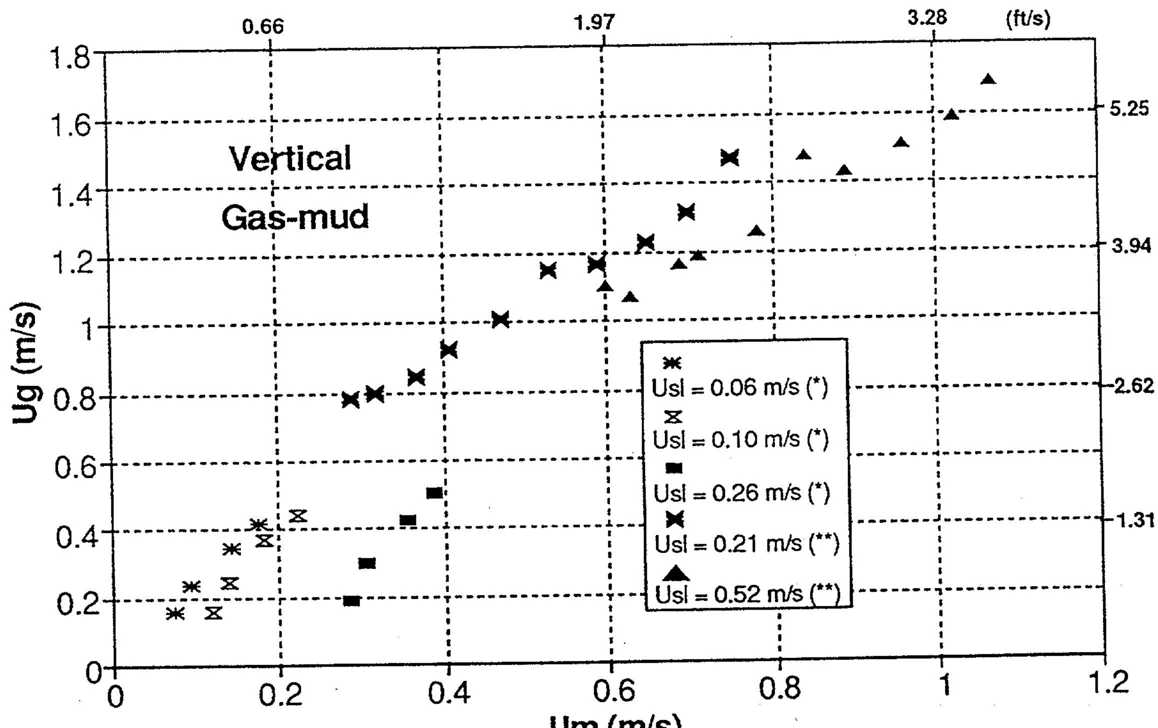


Figure 7 - Plot of true gas velocity vs mixture velocity, gas/mud flow, at vertical position, for different superficial liquid velocities.

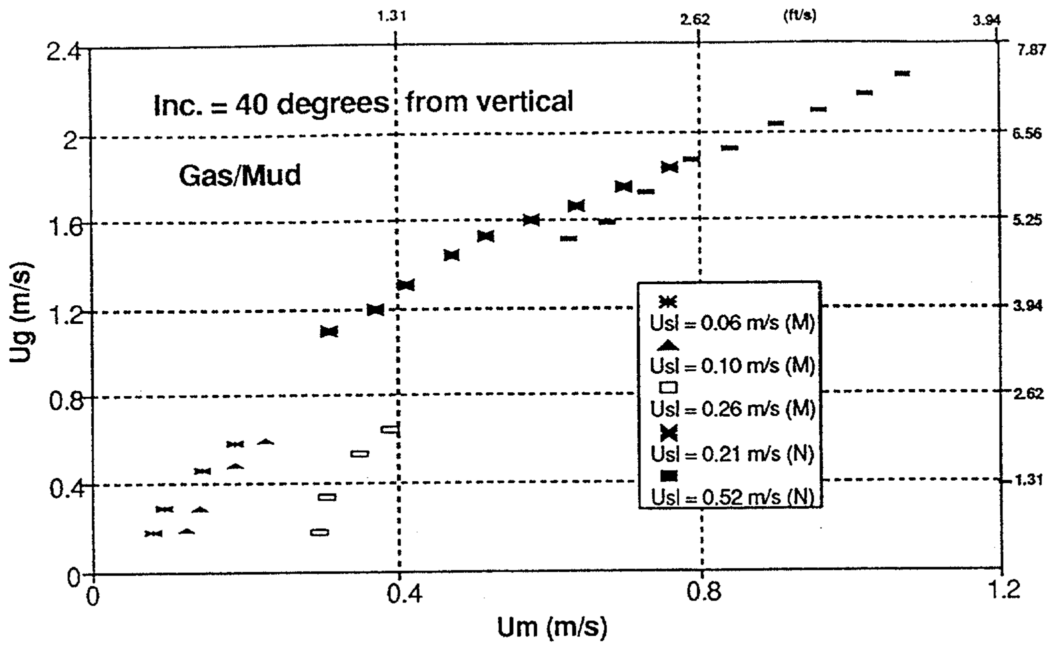


Figure 8 - Same as Fig. 7, for inclination of 40 degrees with vertical.

Another type of plot that is commonly seen in the literature, e.g. Beggs and Brill (1973), and has practical interest in the determination of pressure drops is that of liquid holdup versus inclination angle. Figure 9 shows this type of plot for gas/water flow at the superficial liquid velocity of 0.06 m/s, Figure 10 is for gas/mud flow at superficial liquid velocity of 0.10 m/s, for the different no slip liquid holdups studied (lambda). As already observed, the liquid holdup increases with increasing inclination angles reaching a maximum at approximately 50 degrees. The same tendency was observed for the other configurations.

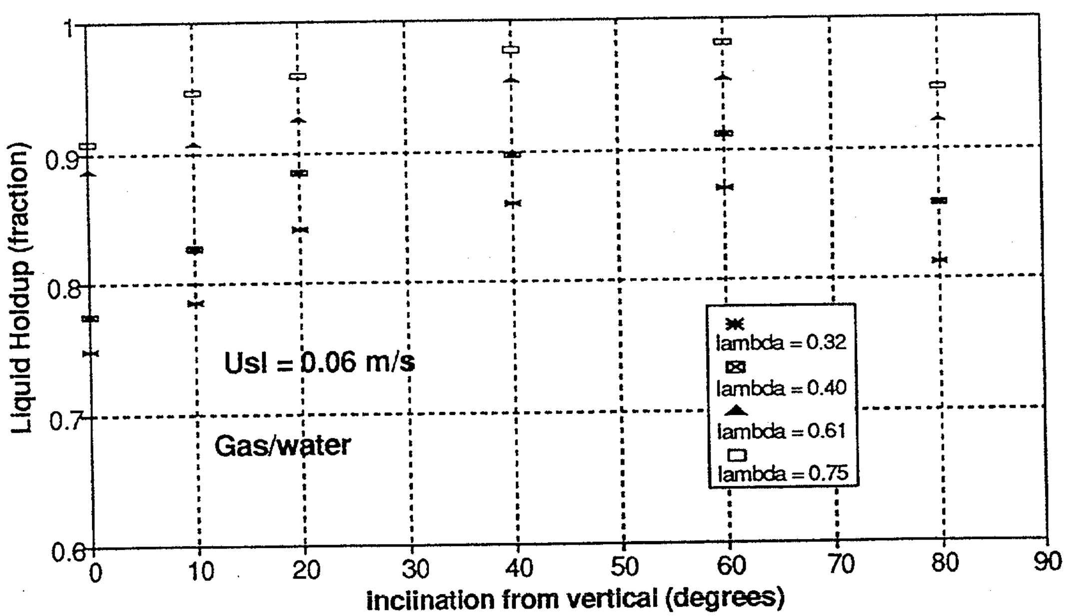


Figure 9 - Liquid holdup vs inclination angle, gas/water flow, at Usl = 0.06 m/s for different non-slip liquid holdups (lambda).

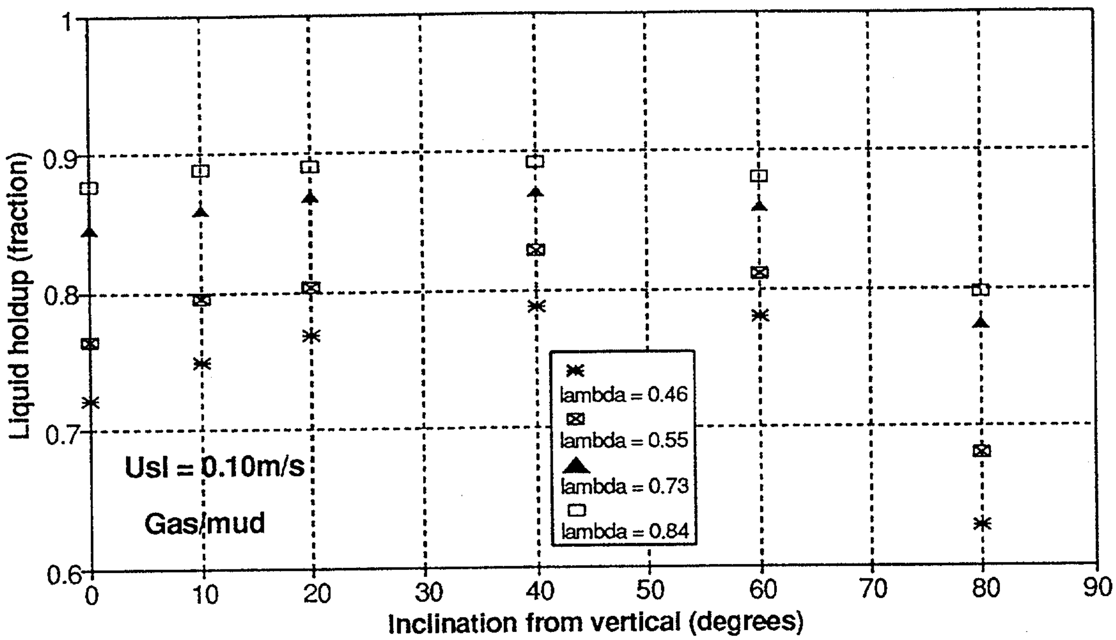


Figure 10 - Same as Fig. 9, for gas/mud flow, Usl = 0.10 m/s.

Conclusions

A successful experimental program on the two-phase flow of gas-liquid mixtures was conducted under conditions representative of well-control operations from which results the following conclusions could be drawn:

1 - For gas/water tests at low mixture velocities and inclination angles varying from 0 to 60 degrees with the vertical, the results agree in some extent with those found in the literature for higher mixture velocities.

2 - For gas/mud mixtures, all inclinations, the true gas velocity was consistently smaller than the results obtained by extrapolating the previous correlations. This behavior might be due to the increase in plastic viscosity of the non-Newtonian fluid (drilling mud) at the lower range of shear stress (agitation).

3 - For the inclined positions tested, the liquid holdup and true gas velocity increased with increasing inclination angles from vertical, until a maximum of approximately 50 degrees.

Discussion: Practical Applications of this Research

It can be seen in Figure 11 a schematic of a horizontal well, where the inclination angle with the vertical is gradually increased from 0 to 90 degrees. Studies that deal with two-phase flow in inclined configurations, with special focus in annular geometries are very rare in the literature. With the current trends indicating an exponential increase in the number of horizontal wells it is necessary to study the flow of liquid and gas that occur in a kick control operation involving all the peculiarities of such wells. The data generated in this experimental work can be used to improve the accuracy of current correlations that are currently used in kick simulators. The drilling personnel will then have a reliable equipment to be trained and the design engineer will have accress to correct parameters required to project the well. The final goal will be achieved if we are able to drill faster and safer, avoiding the disastrous consequences of a blowout.

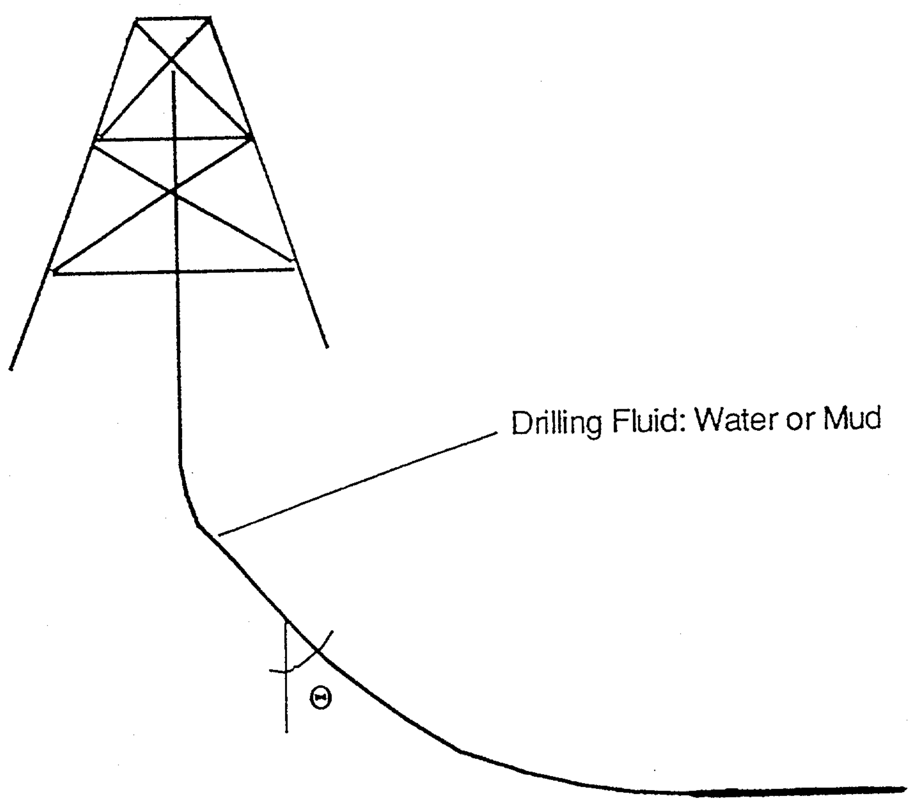


Figure 11 - Schematic of a horizontal well.

Acknowledgement

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Nomenclature

α gas fraction (volumetric)

λ non-slip liquid holdup

ρ_g gas density

ρ_l liquid density

ρ_s density of the flowing mixture

Θ inclination angle of the well axis with the vertical

A_f area open to flow

Di, Do characteristic diameters of the annular space

DP_{tot} pressure drop between the two points in the loop

f two-phase friction factor

H_L liquid holdup

L distance between the points being observed

Q_l liquid flow rate

Q_g gas flow rate

U_g true gas velocity, considering effects of slippage

U_m mixture velocity

U_{sg} gas superficial velocity

U_{sl} liquid superficial velocity